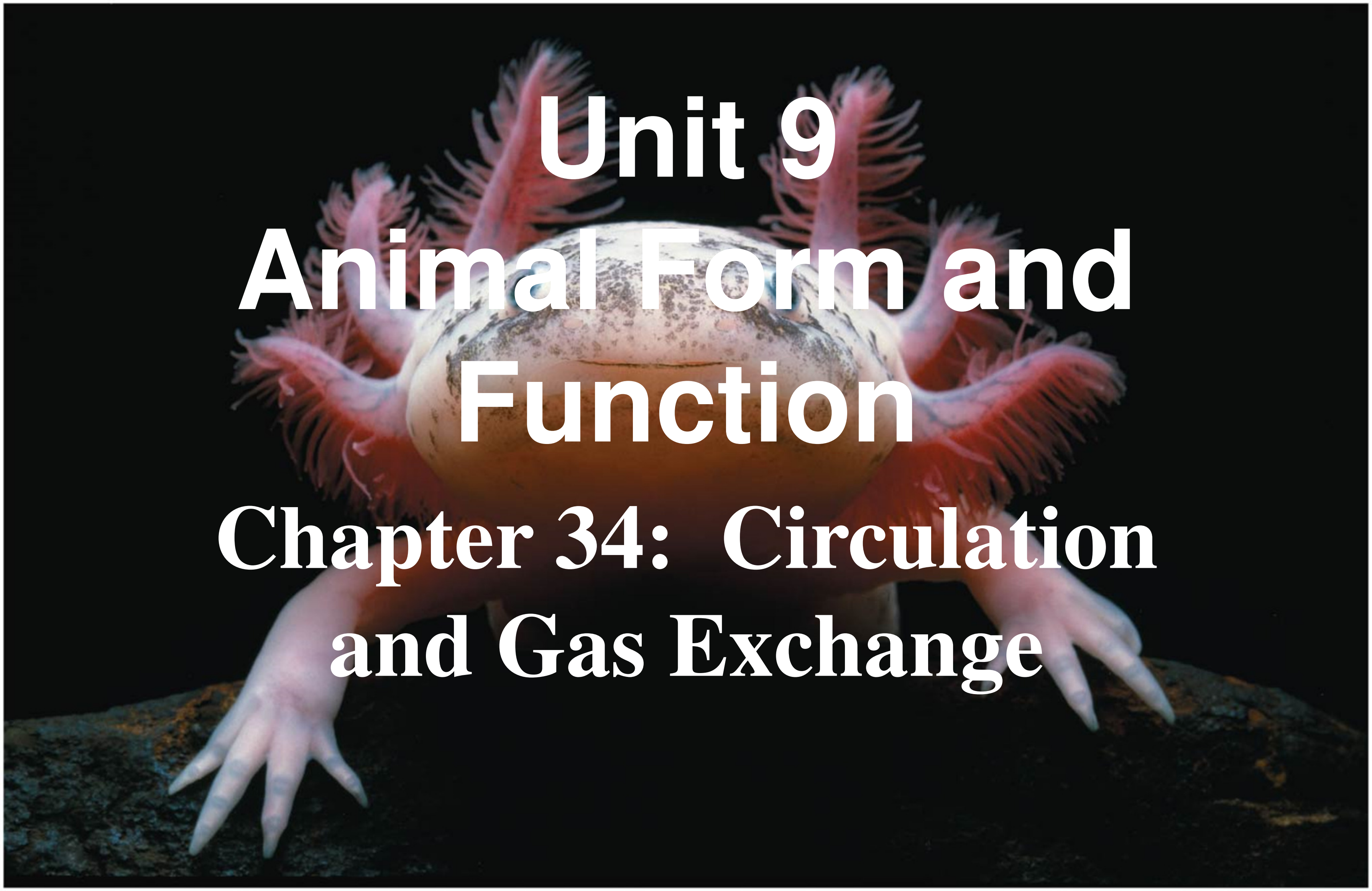


Unit 9 Animal Form and Function

Chapter 34: Circulation and Gas Exchange

Overview: Trading Places

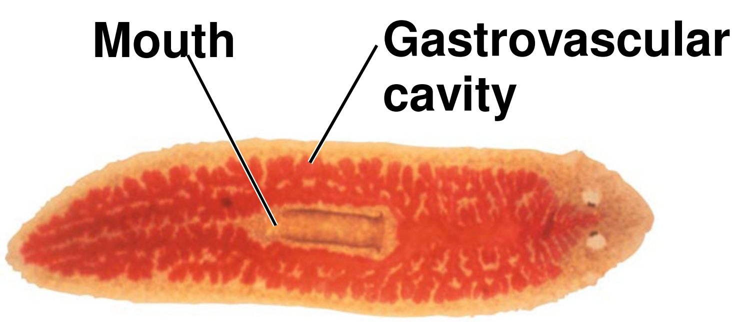
- The resources that animal cells require, such as nutrients and O_2, enter the cytoplasm by crossing the plasma membrane
  - In unicellular organisms, these exchanges occur directly with the environment
  - Most multicellular organisms rely on specialized systems that carry out exchange with the environment and transport materials through the body

Concept 34.1: Circulatory systems link exchange surfaces with cells throughout the body

- Small, nonpolar molecules such as O_2 and CO_2 move between cells and their immediate surroundings by **diffusion**
  - High to low, that's the flow!
  - Diffusion time is proportional to the square of the distance travelled
  - Diffusion is only efficient over small distances
- In small or thin animals, cells can exchange materials directly with the surrounding medium
- In most animals, cells exchange materials with the environment via a fluid-filled circulatory system

Gastrovascular Cavities

- Some animals lack a circulatory system
  - Some cnidarians, such as jellies, have elaborate **gastrovascular cavities**
    - A gastrovascular cavity functions in both digestion and distribution of substances throughout the body
  - Flatworms have a gastrovascular cavity and a flat body shape to optimize diffusional exchange with the environment

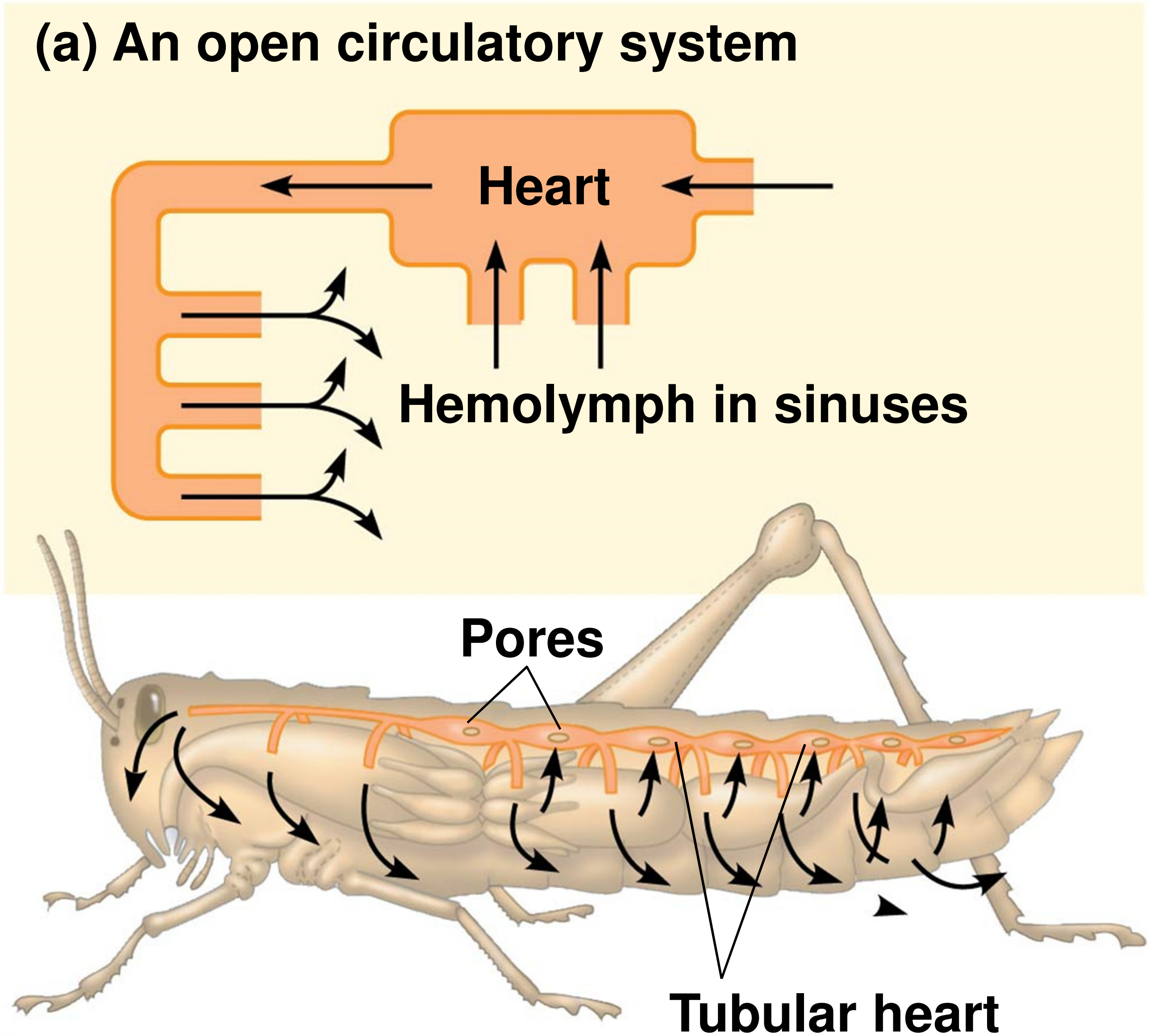


Open and Closed Circulatory Systems

- A circulatory system has a
  - Circulatory fluid
  - Set of interconnecting vessels
  - Muscular pump, the **heart**
    - Powers circulation by using metabolic energy to elevate the hydrostatic pressure of the hydrostatic fluid
- All circulatory systems are either open or closed

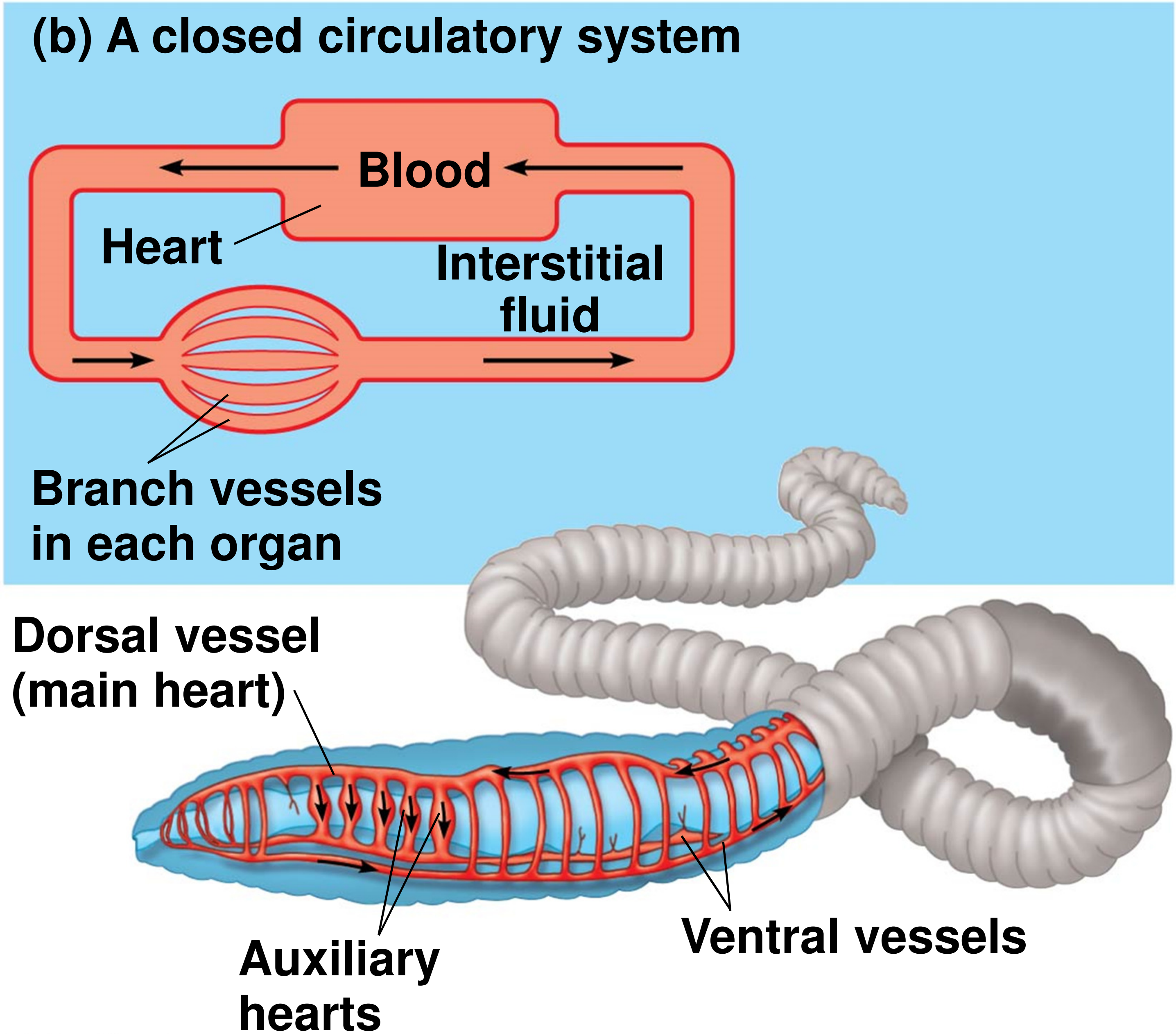
- In insects, other arthropods, and some molluscs, circulatory fluid bathes the organs directly in an **open circulatory system**
  - No distinction between circulatory fluid and interstitial fluid
    - This general body fluid is called **hemolymph**
  - Lower hydrostatic pressure is less costly in terms of energy expenditure

Figure 34.3a


(a) An open circulatory system
Heart
Hemolymph in sinuses
Pores
Tubular heart

- In **closed circulatory systems** the circulatory fluid called **blood** is confined to vessels and is distinct from interstitial fluid
  - Found in annelids, most cephalopods, and all vertebrates
  - One or more hearts pump blood through the vessels
  - Chemical exchange occurs between blood and interstitial fluid and between interstitial fluid and body cells
  - Relatively high blood pressure enables effective delivery of O_2 and nutrients to cells of larger and more active animals
  - Well suited to regulating distribution of blood to different organs

Figure 34.3b


(b) A closed circulatory system
Blood
Heart
Interstitial fluid
Branch vessels in each organ
Dorsal vessel (main heart)
Auxiliary hearts
Ventral vessels

Organization of Vertebrate Circulatory Systems

- Humans and other vertebrates have a closed circulatory system called the **cardiovascular system**
- The three main types of blood vessels are
  - Arteries
  - Veins
  - Capillaries
- Blood flow is one-way in these vessels

- **Arteries** carry blood <u>away</u> from the heart to various organs
  - Branch into *arterioles* which then convey blood to microscopic vessels with thin, porous walls called **capillaries**
  - Networks of capillaries called **capillary beds** are the sites of chemical exchange between the blood and interstitial fluid
- Capillaries converge into *venules* **which** converge into **veins**
  - Carry blood back to the heart

- Arteries and veins are distinguished by the direction of blood flow
  - Not by O_2 content!

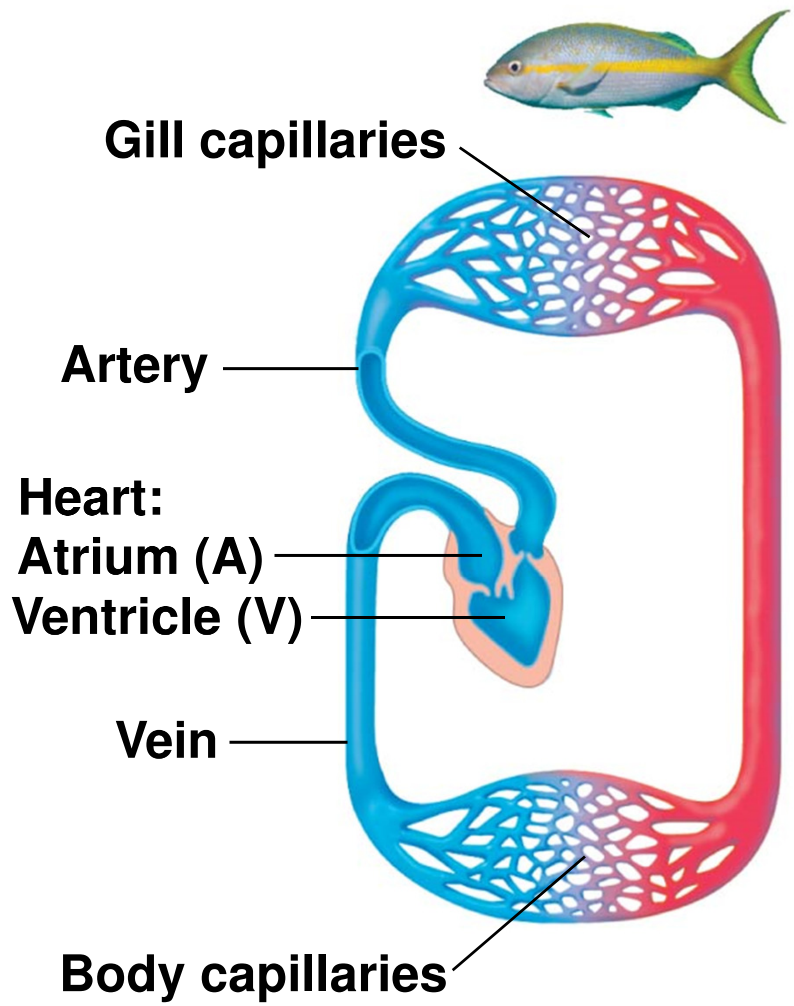
- Vertebrate hearts contain two or more chambers
- Blood enters through an **atrium** and is pumped out through a **ventricle**

Single Circulation

- Bony fishes, rays, and sharks have single circulation with a two-chambered heart
- In **single circulation**, blood passes through the heart once in each complete circuit
  - Blood leaving the heart passes through two capillary beds before returning

Figure 34.4a

(a) Single circulation: fish



Key

- Oxygen-rich blood
- Oxygen-poor blood

Double Circulation

- Amphibians, reptiles, and mammals have **double circulation**
  - Oxygen-poor and oxygen-rich blood is pumped separately from the right and left sides of the heart
  - 2 circuits
    1. Gas exchange circuit
    2. Systemic circuit
  - Having both pumps within a heart simplifies coordination of the pumping cycle
  - Double circulation maintains higher blood pressure in the organs than does single circulation

- The right side of the heart delivers oxygen-poor blood to capillary beds of the gas exchange tissues via the **gas exchange circuit**
  - Net movement of O_2 into blood and CO_2 out of blood
  - 2 types of gas exchange circuits
    - *Pulmonary circuit*
      - Capillary beds are all in the lungs
      - Ex: Reptiles and mammals
    - *Pulmocutaneous circuit*
      - Capillary beds are both the lungs and skins
      - Ex: Amphibians

- Oxygenated blood then enters the left side of the heart
  - Blood is propelled to capillary beds and in organs and tissues throughout body
  - O_2, CO_2, nutrients, and wastes are exchanged
  - Oxygen poor blood returns to heart, completing the **systemic circuit**
    - Supplies oxygenated blood to and carries deoxygenated blood away from organs and tissues throughout the body

Figure 34.4b

(b) Double circulation: amphibian

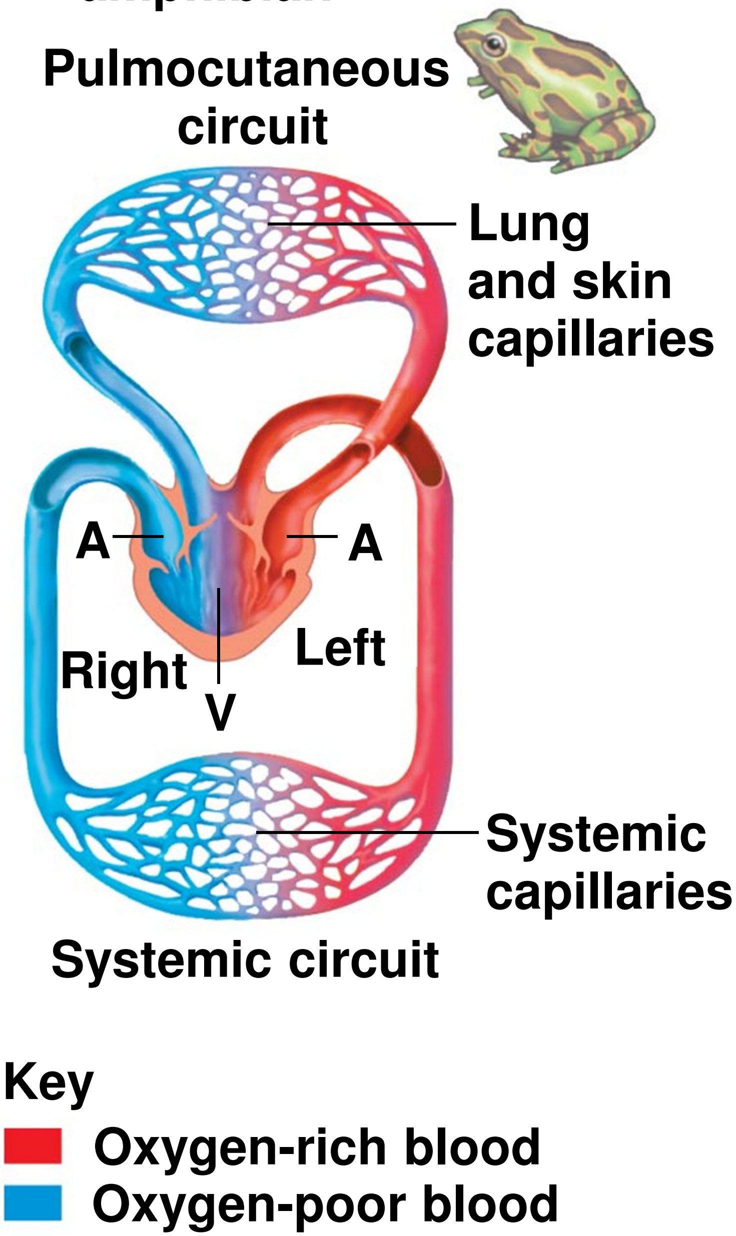
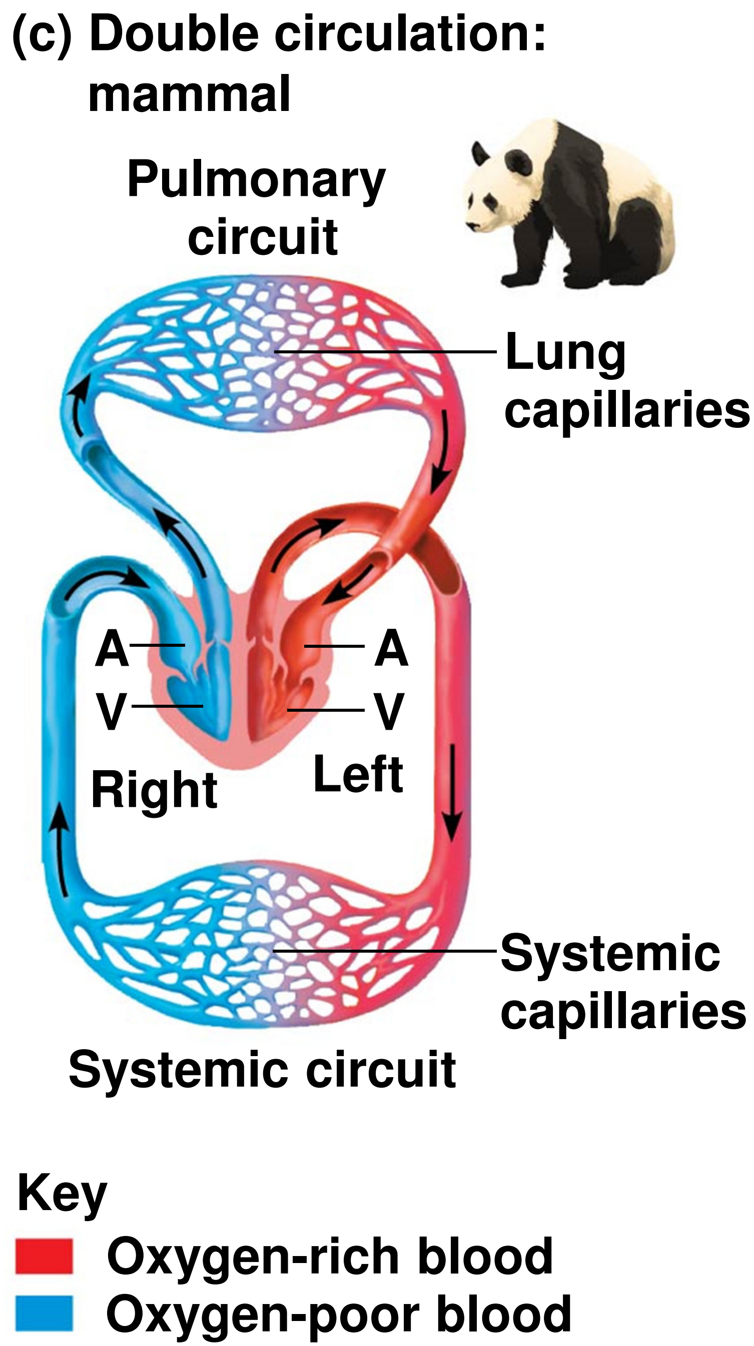


Figure 34.4c


(c) Double circulation: mammal
Pulmonary circuit
Lung capillaries
A
V
A
V
Right
Left
Systemic capillaries
Systemic circuit
Key
Oxygen-rich blood
Oxygen-poor blood

Evolutionary Variation in Double Circulation

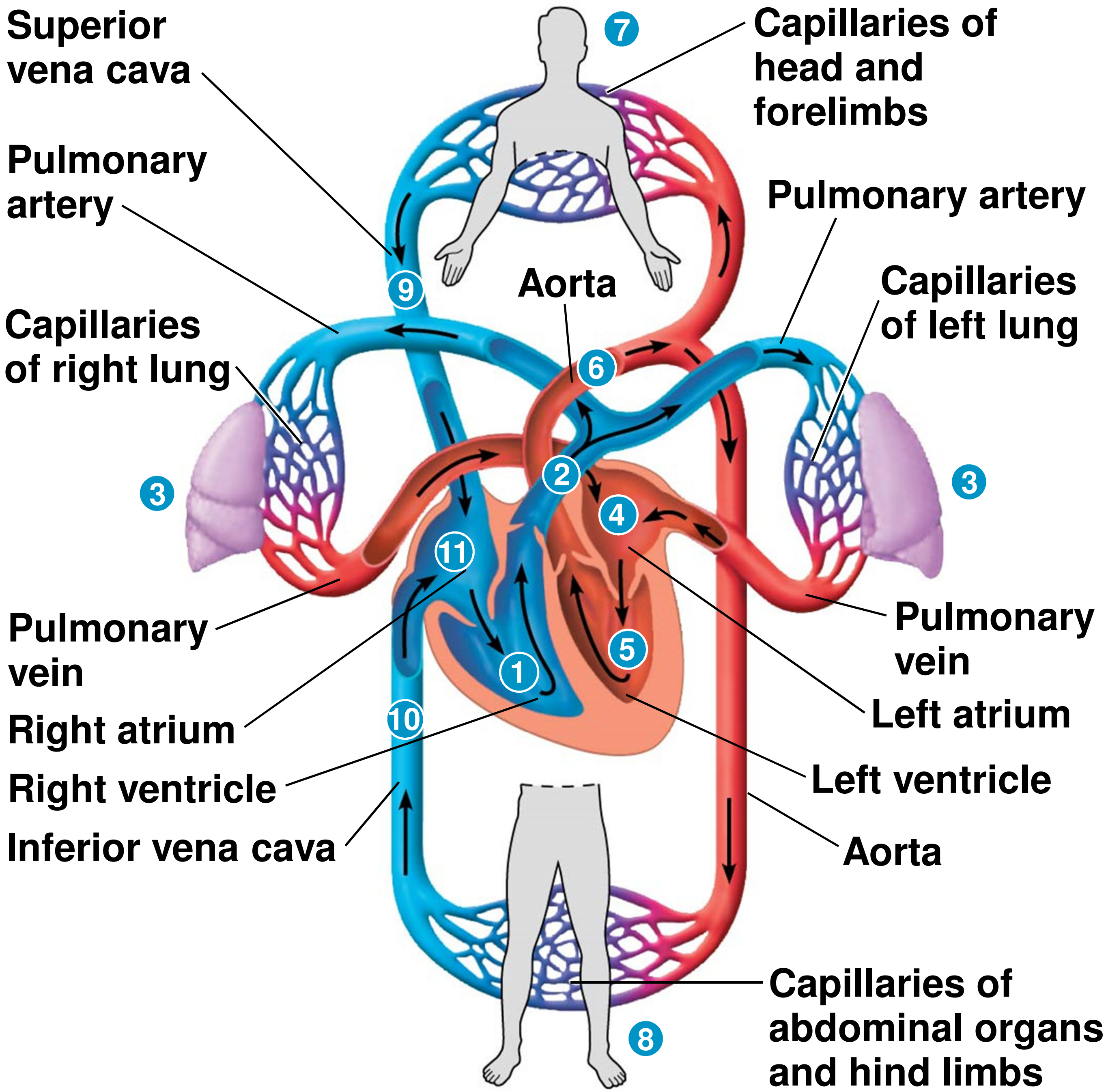
- Some vertebrates with double circulation are intermittent breathers
- These animals have adaptations that enable the circulatory system temporarily to bypass the lungs
  - Frogs and other amphibians have a three-chambered heart: two atria and one ventricle
  - Turtles, snakes, and lizards have a three-chambered heart: two atria and one ventricle with an incomplete septum
  - In alligators, caimans, and other crocodilians a complete septum divides the ventricle

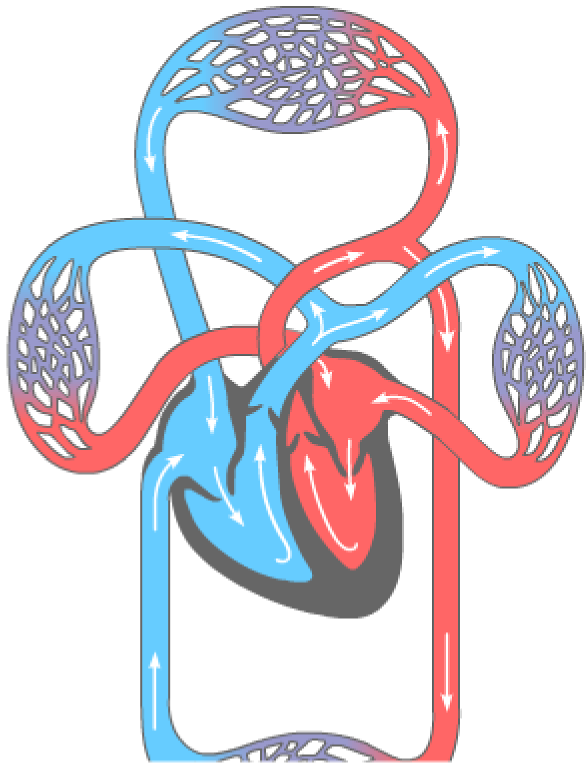
- Mammals and birds have a four-chambered heart with two atria and two ventricles
  - The left side of the heart pumps and receives only oxygen-rich blood
  - The right side receives and pumps only oxygen-poor blood
    - There is no mechanism to vary relative blood flow to the lungs and body
- Mammals and birds are endotherms and require more energy and therefore more O_2 than ectotherms

Concept 34.2: Coordinated cycles of heart contraction drive double circulation in mammals

- Flow of blood in mammalian circulatory system
  - Right ventricle pumps blood to lungs via the pulmonary arteries
    - Picks up O_2, drops off CO_2
  - Oxygen-rich blood travels back to heart via pulmonary veins
  - Blood enters left atrium and flows to left ventricle
  - Blood is pumped to body tissues via the aorta
    - Delivers O_2 and picks up CO_2
  - Oxygen-poor blood travels back to heart via superior and inferior vena cava
  - Blood empties into right atrium and then flows into right ventricle

Figure 34.5


Superior vena cava
Pulmonary artery
Capillaries of right lung
Pulmonary vein
Right atrium
Right ventricle
Inferior vena cava
Capillaries of head and forelimbs
Pulmonary artery
Aorta
Capillaries of left lung
Pulmonary vein
Left atrium
Left ventricle
Aorta
Capillaries of abdominal organs and hind limbs
1
2
3
3
4
5
6
7
8
9
10
11



Animation: Path of Blood Flow
Right click slide / Select play

The Mammalian Heart: *A Closer Look*

- When the heart relaxes, its chambers fill with blood
  - Atria have relatively thin walls and serve as collection chambers for blood returning to the heart
- When the heart contracts, it pumps blood
  - The ventricles are more muscular and contract much more forcefully than the atria
- One complete sequence of pumping and filling is called the **cardiac cycle**
  - Contraction phase is called **systole**
  - Relaxation phase is called **diastole**

- The volume of blood each ventricle pumps per minute is called the cardiac output
  - Cardiac output is determined by 2 factors
    - Heart rate (also called the pulse)
      - Number of beats per minute
    - *Stroke volume*
      - Amount of blood pumped in a single contraction

- Four valves prevent backflow of blood in the heart
  - The **atrioventricular (AV) valves** separate each atrium and ventricle
  - The **semilunar valves** control blood flow to the aorta and the pulmonary artery from the ventricles
- The "lub-dup" sound of a heart beat is caused by the recoil of blood against the AV valves (lub) then against the semilunar (dup) valves
- Backflow of blood through a defective valve causes a **heart murmur**

Figure 34.6

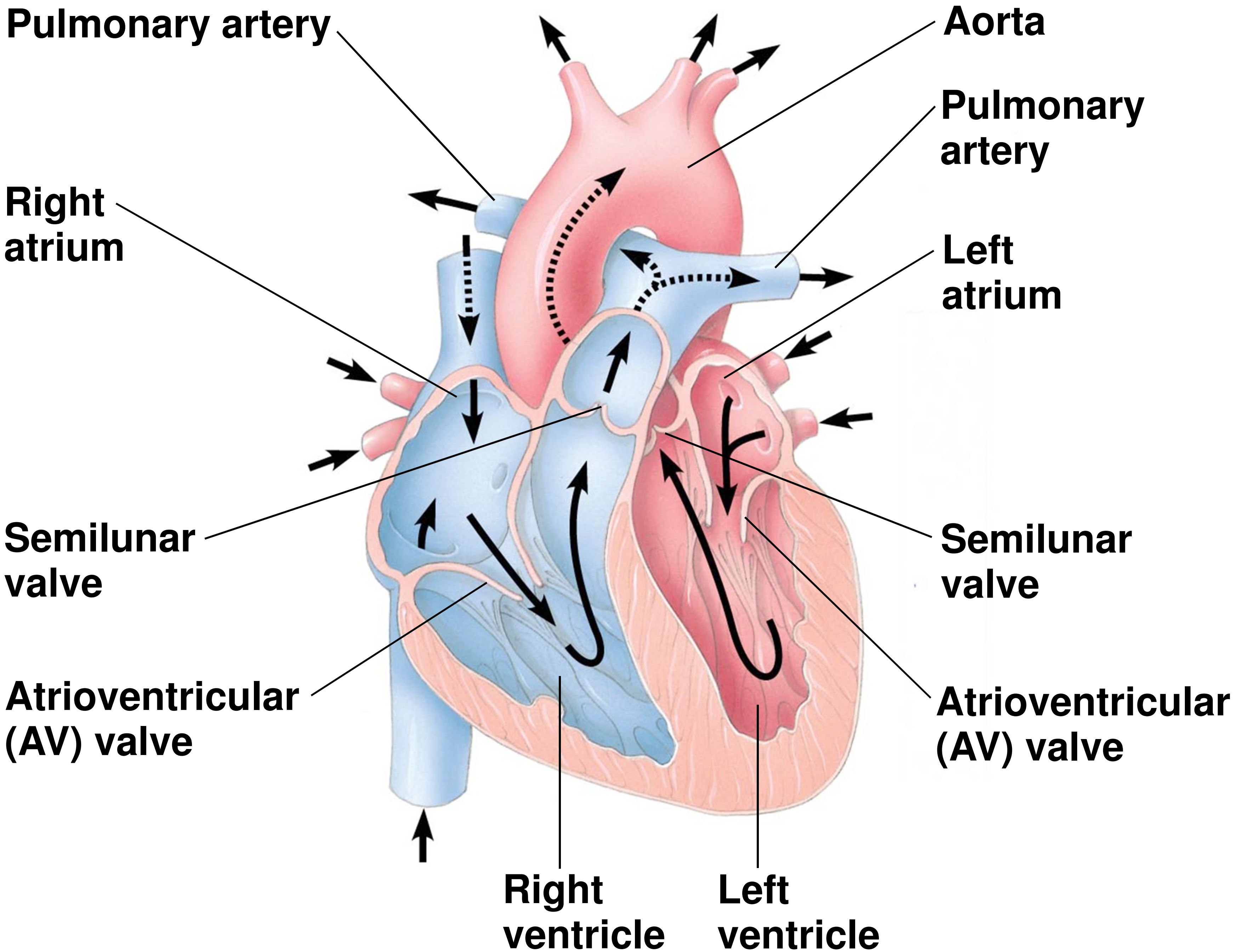
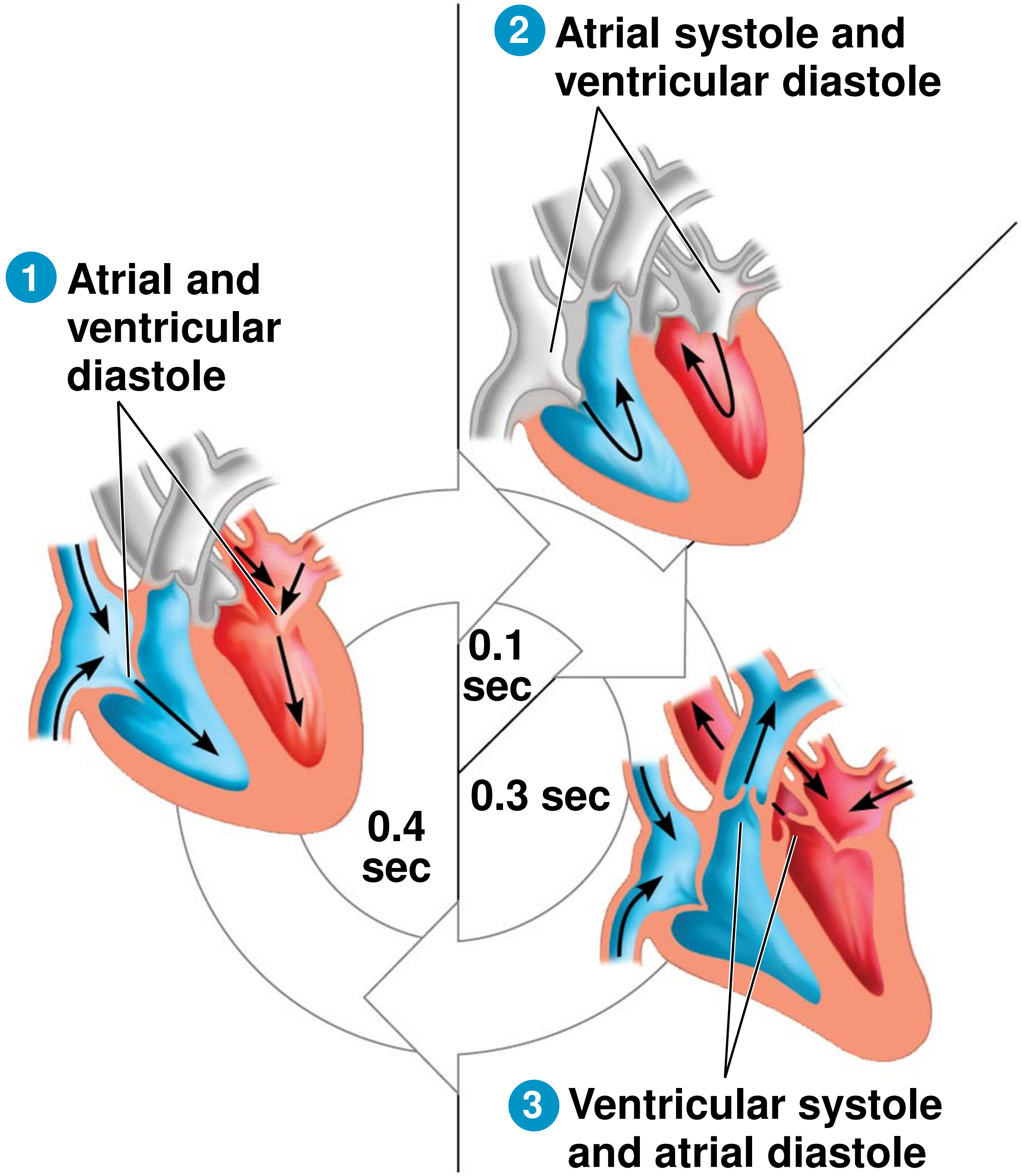

Pulmonary artery
Aorta
Pulmonary
artery
Right
atrium
Left
atrium
Semilunar
valve
Semilunar
valve
Atrioventricular
(AV) valve
Atrioventricular
(AV) valve
Right
ventricle
Left
ventricle

Figure 34.7-3



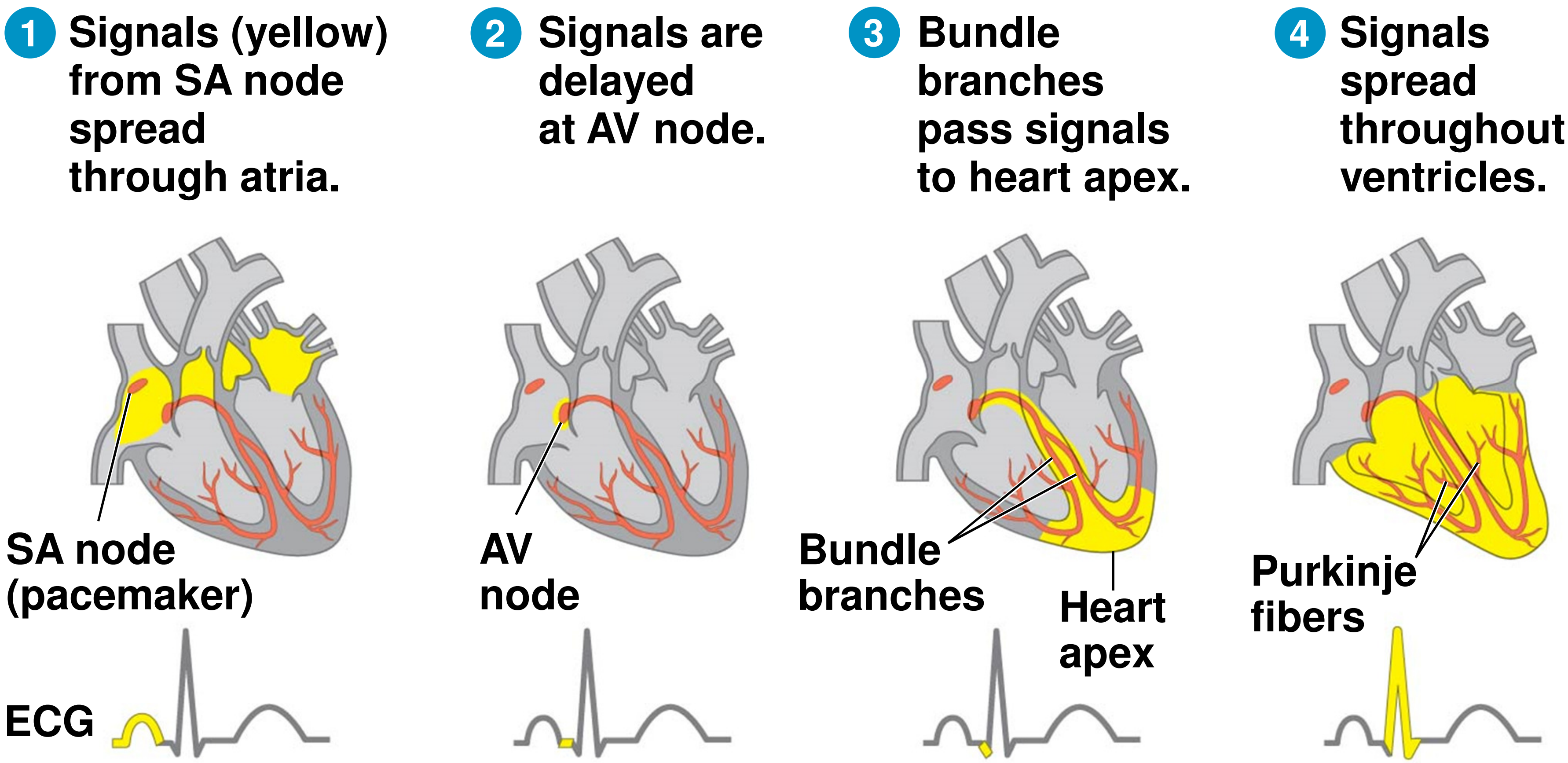
1 Atrial and ventricular diastole
2 Atrial systole and ventricular diastole
3 Ventricular systole and atrial diastole
0.1 sec
0.3 sec
0.4 sec

Maintaining the Heart's Rhythmic Beat

- Some cardiac muscle cells are autorhythmic, meaning they contract without any signal from the nervous system
  - The **sinoatrial (SA) node**, or pacemaker, sets the rate and timing at which all other cardiac muscle cells contract
    - The SA node produces electrical impulses that spread rapidly through the heart
    - Can be recorded as an **electrocardiogram** (**ECG** or **EKG**)

- Impulses from the SA node travel to the **atrioventricular (AV) node**
  - At the AV node, the impulses are delayed
    - Allows atria to empty completely before ventricles contract
- Signals then travel to the Purkinje fibers that make the ventricles contract

Figure 34.8-4


1 Signals (yellow) from SA node spread through atria.
2 Signals are delayed at AV node.
3 Bundle branches pass signals to heart apex.
4 Signals spread throughout ventricles.
SA node (pacemaker)
AV node
Bundle branches
Heart apex
Purkinje fibers
ECG

- The pacemaker is regulated by two portions of the nervous system
  - Sympathetic division
    - Speeds up the pacemaker
  - Parasympathetic division
    - Slows down the pacemaker
- The pacemaker is also regulated by hormones and temperature
  - Ex: Epinephrine (Fight-or-flight hormone)
    - Causes heart rate to increase

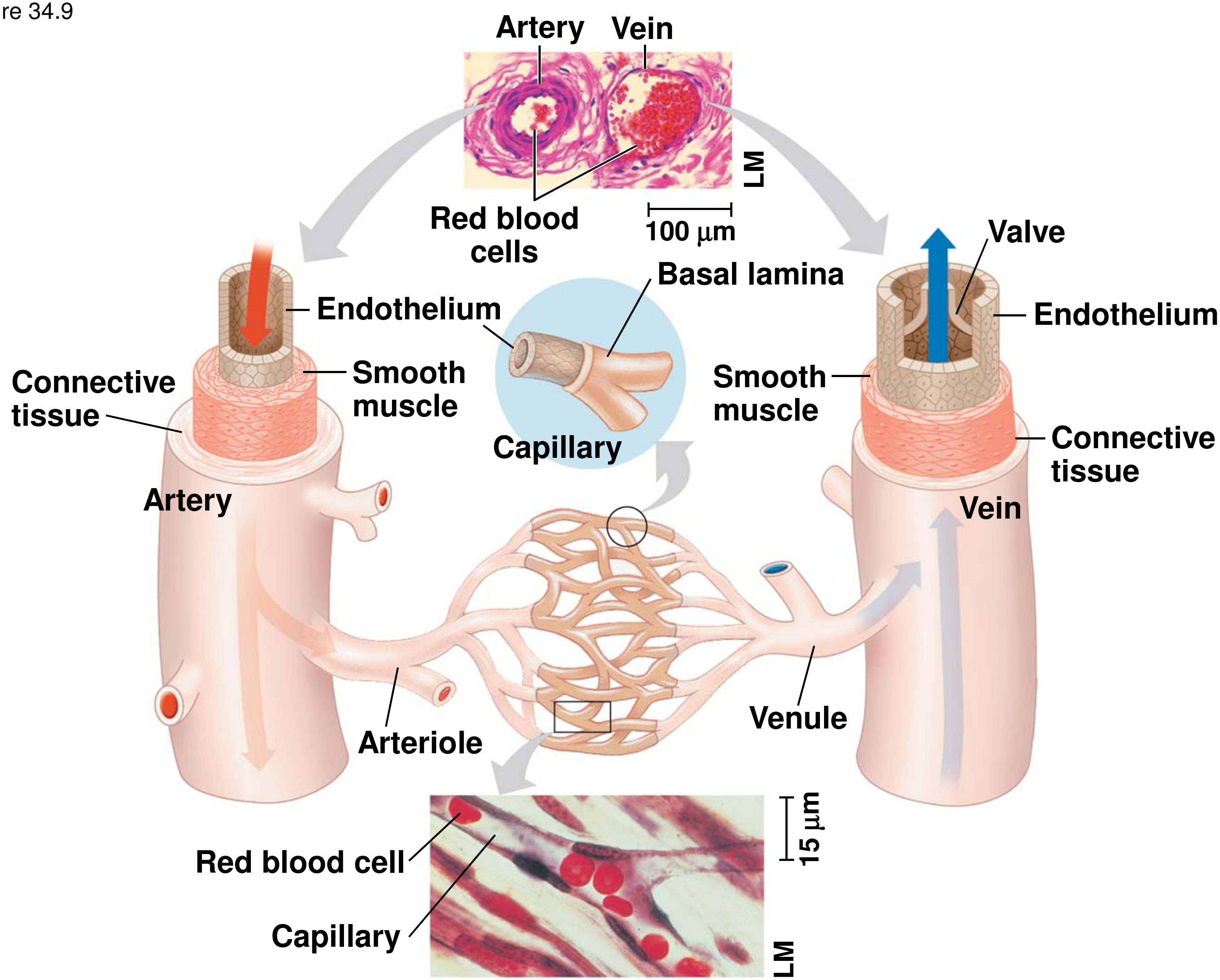
Concept 34.3: Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels

Blood Vessel Structure and Function

- A vessel's cavity is called the central lumen
- The epithelial layer that lines blood vessels is called the **endothelium**
  - The endothelium is smooth and minimizes resistance to blood flow

- Capillaries are the smallest blood vessels and have thin walls
    - To facilitate the exchange of substances
- Arteries have thicker walls than veins
    - To accommodate the high pressure of blood pumped from the heart
- Veins contain valves
    - To maintain unidirectional flow of blood despite the low blood pressure found here

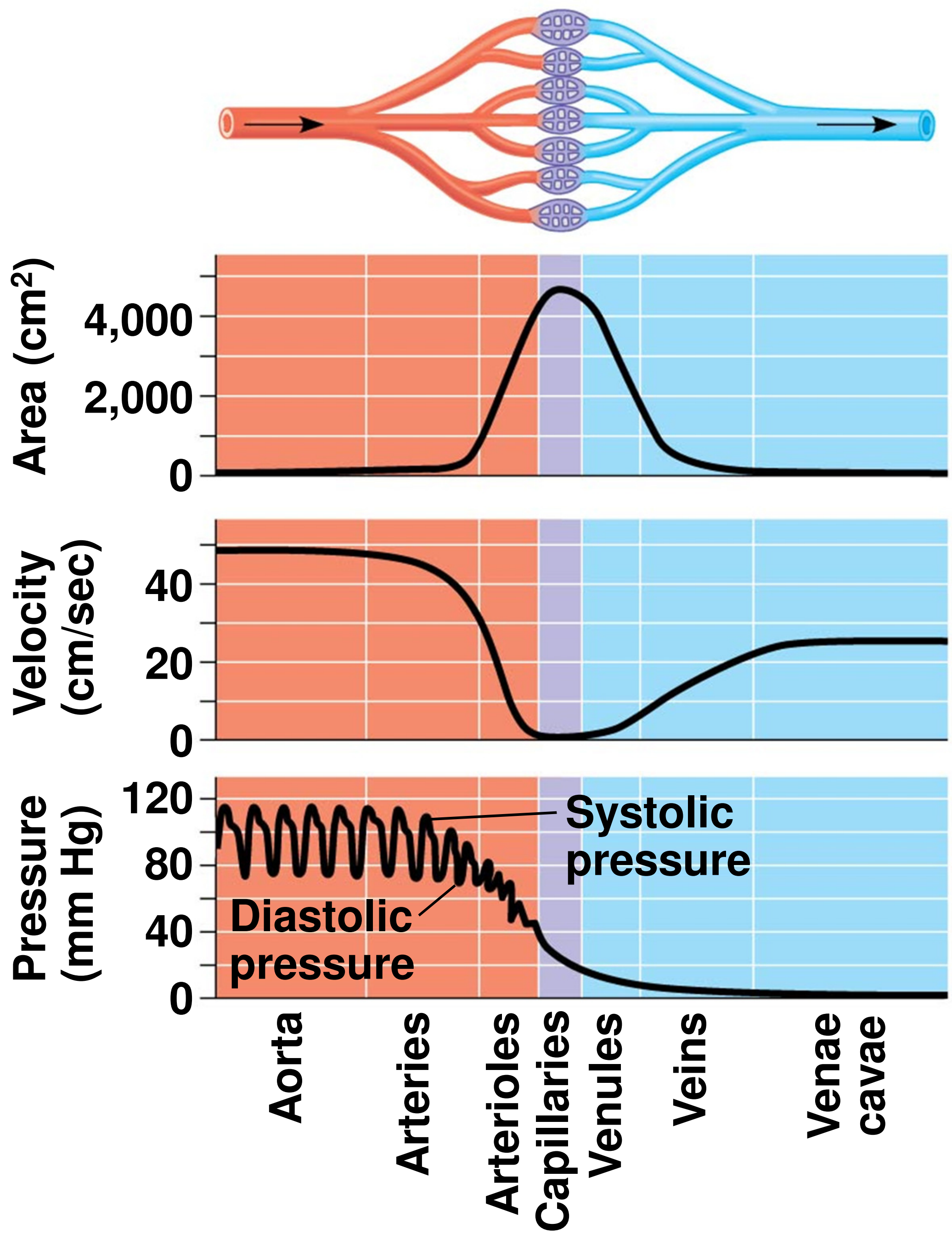
Figure 34.9


Artery
Vein
Red blood cells
LM
100 µm
Valve
Basal lamina
Endothelium
Endothelium
Smooth muscle
Smooth muscle
Connective tissue
Connective tissue
Capillary
Artery
Vein
Arteriole
Venule
Red blood cell
Capillary
15 µm
LM

Blood Flow Velocity

- Blood vessel diameter influences blood flow
- Velocity of blood flow is slowest in the capillary beds
  - As a result of the high resistance and large total cross-sectional area
    - Roughly 7 billion capillaries in human body
  - Slow blood flow in capillaries is necessary for exchange of materials

Figure 34.10



Area (cm^2)
4,000
2,000
0
Velocity (cm/sec)
40
20
0
Pressure (mm Hg)
120
80
40
0
Systolic pressure
Diastolic pressure
Aorta
Arteries
Arterioles
Capillaries
Venules
Veins
Venae cavae

Blood Pressure

- Blood flows from areas of higher pressure to areas of lower pressure
- Blood pressure exerts a force in all directions

Changes in Blood Pressure During the Cardiac Cycle

- **Systole** is the contraction phase of the cardiac cycle
  - Pressure at the time of ventricle contraction is called *systolic pressure*
  - Arterial blood pressure is highest during systole
- **Diastole** is the relaxation phase of the cardiac cycle
  - *Diastolic pressure* is the blood pressure when the ventricles are relaxed
  - Lower than systolic pressure
- Each spike in blood pressure caused by a contraction of a ventricle stretches the arteries
  - They rhythmic bulging of the artery walls with each heartbeat is your **pulse**

Maintenance of Blood Pressure

- Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles
- **Vasoconstriction** is the contraction of smooth muscle in arteriole walls
  - Increases blood pressure
- **Vasodilation** is the relaxation of smooth muscles in the arterioles
  - Causes blood pressure to fall
- Vasoconstriction and vasodilation help maintain adequate blood flow as the body's demands change

Capillary Function

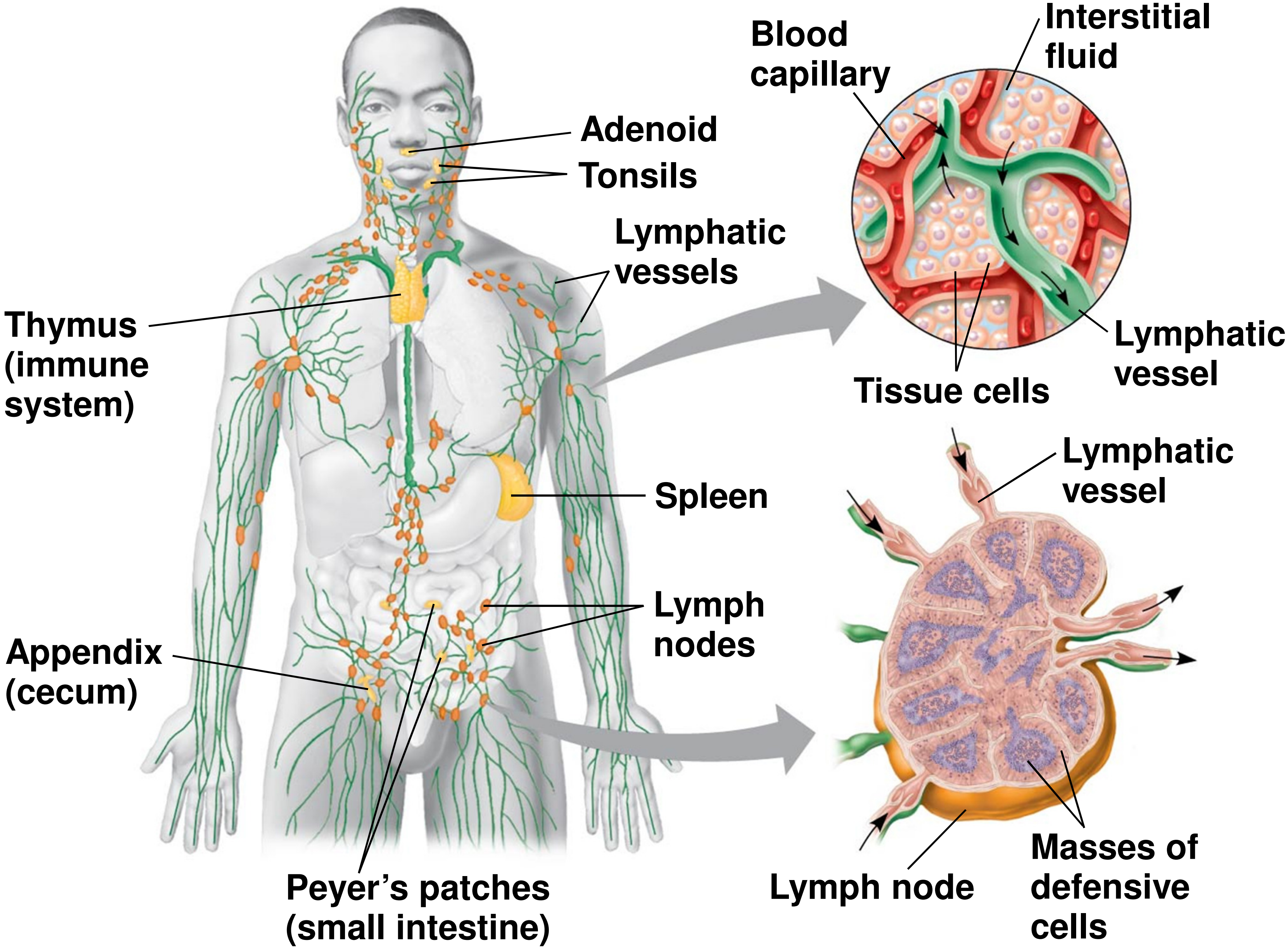
- Blood flows through only 5–10% of the body’s capillaries at a time
- Capillaries in major organs are usually filled to capacity
- Blood supply varies in many other sites
  - Blood flow to skin is regulated to help control body temperature
  - During exercise, blood is diverted from digestive tract to skeletal muscles and skin

- Two mechanisms alter blood flow in capillary beds
  - Vasoconstriction or vasodilation of the arteriole that supplies a capillary bed
  - Precapillary sphincters, rings of smooth muscle at the capillary bed entrance, open and close to regulate passage of blood
- Critical exchange of substances takes place across the thin walls of the capillaries
- Blood pressure tends to drive fluid out of the capillaries

Fluid Return by the Lymphatic System

- The **lymphatic system** returns fluid, called **lymph**, that leaks out from the capillary beds
- **Lymph nodes** are organs that filter lymph and play an important role in the body's <u>defense</u>

Figure 34.12


Adenoid
Tonsils
Lymphatic vessels
Thymus (immune system)
Spleen
Lymph nodes
Appendix (cecum)
Peyer's patches (small intestine)
Blood capillary
Interstitial fluid
Lymphatic vessel
Tissue cells
Lymphatic vessel
Lymph node
Masses of defensive cells

Concept 34.4: Blood components function in exchange, transport, and defense

- With open circulation, the fluid that is pumped comes into direct contact with all cells and has the same composition as interstitial fluid
- The closed circulatory systems of vertebrates contain blood, which can be much more highly specialized

Blood Composition and Function

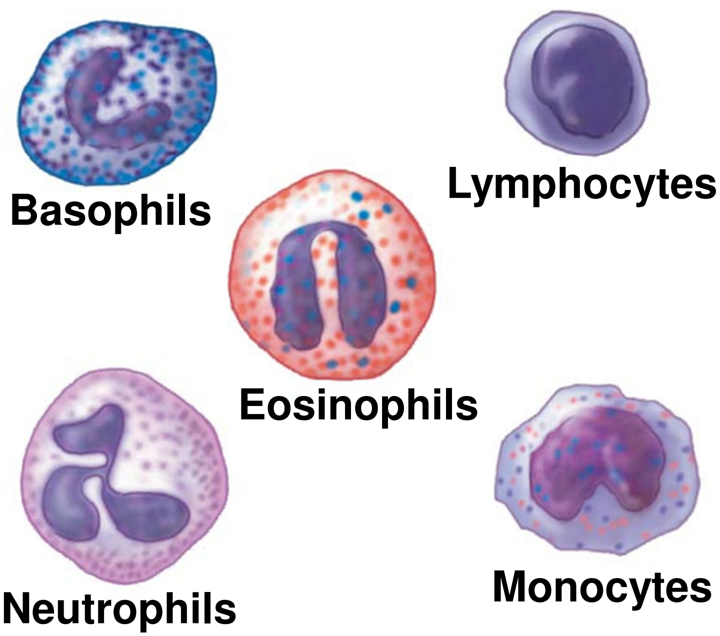
- Blood is a connective tissue consisting of cells suspended in a liquid matrix called **plasma**
- Blood plasma is about 90% water
  - Among its solutes are inorganic salts in the form of dissolved ions, sometimes called electrolytes
- Plasma proteins influence blood pH, osmotic pressure, and viscosity
- Particular plasma proteins function in lipid transport, immunity, and blood clotting

- Blood contains two classes of cells
  - Red blood cells (erythrocytes) transport O_2
  - White blood cells (leukocytes) function in defense
- **Platelets**, a third cellular element, are fragments of cells that are involved in clotting

Figure 34.13a

Plasma 55%	
Constituent	**Major functions**
Water	Solvent for carrying other substances
Ions (blood electrolytes) Sodium Potassium Calcium Magnesium Chloride Bicarbonate	Osmotic balance, pH buffering, and regulation of membrane permeability
Plasma proteins	
Albumin	Osmotic balance, pH buffering
Fibrinogen	Clotting
Immunoglobulins (antibodies)	Defense
Substances transported by blood Nutrients (such as glucose, fatty acids, vitamins) Waste products of metabolism Respiratory gases (O_2 and CO_2) Hormones	

Figure 34.13b

Cellular elements 45%		
Cell type	**Number** per μL (mm^3) of blood	**Functions**
Leukocytes (white blood cells) 	5,000–10,000	Defense and immunity
Platelets 	250,000–400,000	Blood clotting
Erythrocytes (red blood cells) 	5,000,000–6,000,000	Transport of O_2 and some CO_2

Erythrocytes

- Red blood cells, or **erythrocytes**, are by far the most numerous blood cells
  - Their shape increases surface area!
  - Enhances rate of diffusion of O_2 across membrane
- In mammals, mature erythrocytes lack nuclei
  - Leaves more space for **hemoglobin**, the iron-containing protein that transports oxygen
- **Sickle-cell disease** is caused by abnormal hemoglobin that distorts erythrocytes into a sickle shape

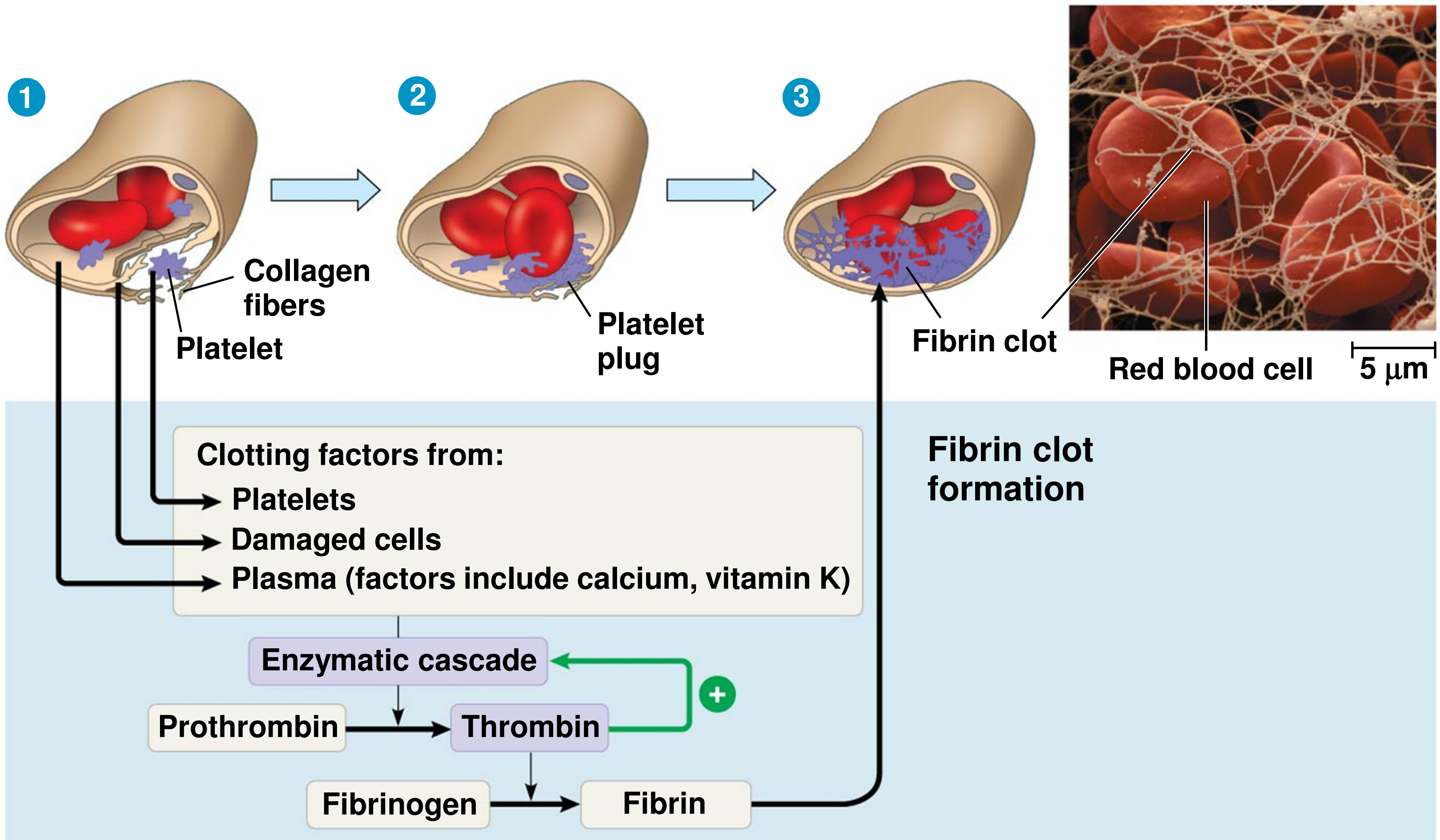
Leukocytes

- There are five major types of white blood cells, or **leukocytes**
  - Basophils, lymphocytes, eosinophils, neutrophils, monocytes
- They function in defense
  - Fight infections by engulfing bacteria and debris or by mounting immune responses against foreign substances
- They are found both in and outside of the circulatory system

Platelets

- Platelets are fragments of cells and function in blood clotting
- Coagulation is the formation of a solid clot from liquid blood
- Platelets release clotting factors that lead to the formation of the enzyme thrombin
  - Drives clotting to completion through positive feedback
- In hemophilia, a step in the clotting process is blocked
  - Excessive bleeding and bruising
- A blood clot formed within a blood vessel is called a **thrombus** and can block blood flow

Figure 34.15


1
2
3
Collagen fibers
Platelet
Platelet plug
Fibrin clot
Red blood cell
5 µm
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)
Enzymatic cascade
Prothrombin
Thrombin
+
Fibrinogen
Fibrin
Fibrin clot formation

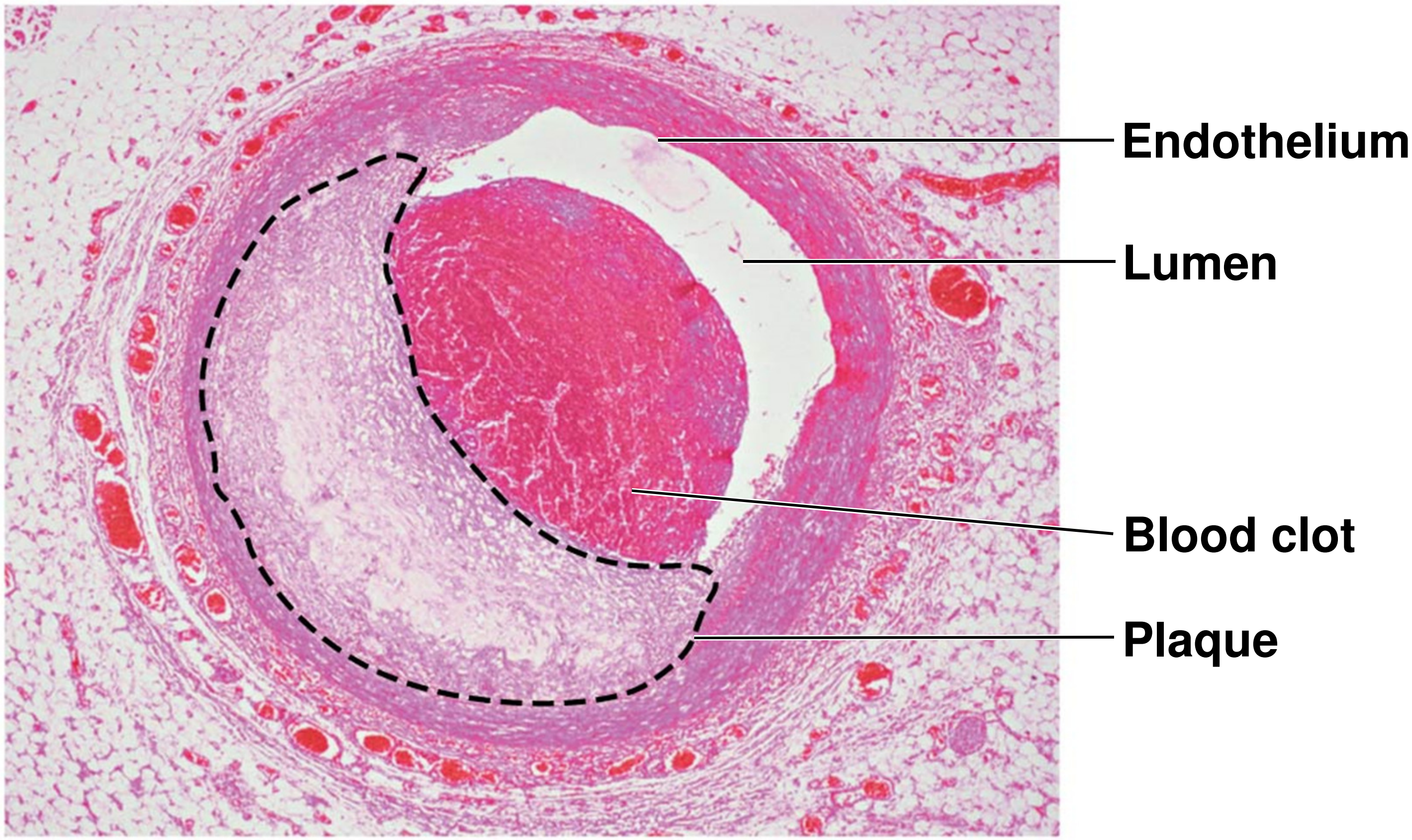
Cardiovascular Disease

- Cardiovascular diseases are disorders of the heart and the blood vessels
- Cholesterol, a steroid, helps maintain normal membrane fluidity
  - Circulating cholesterol and inflammation contribute to cardiovascular diseases

Atherosclerosis, Heart Attacks, and Stroke

- **Atherosclerosis** is the hardening of arteries by fatty deposits
  - A fatty deposit called a plaque grows
  - Artery walls become thick and stiff and the obstruction of the artery increases
    - Reduces diameter available for blood flow
  - When untreated, often results in
    - Heart attack
    - Stroke

Figure 34.16



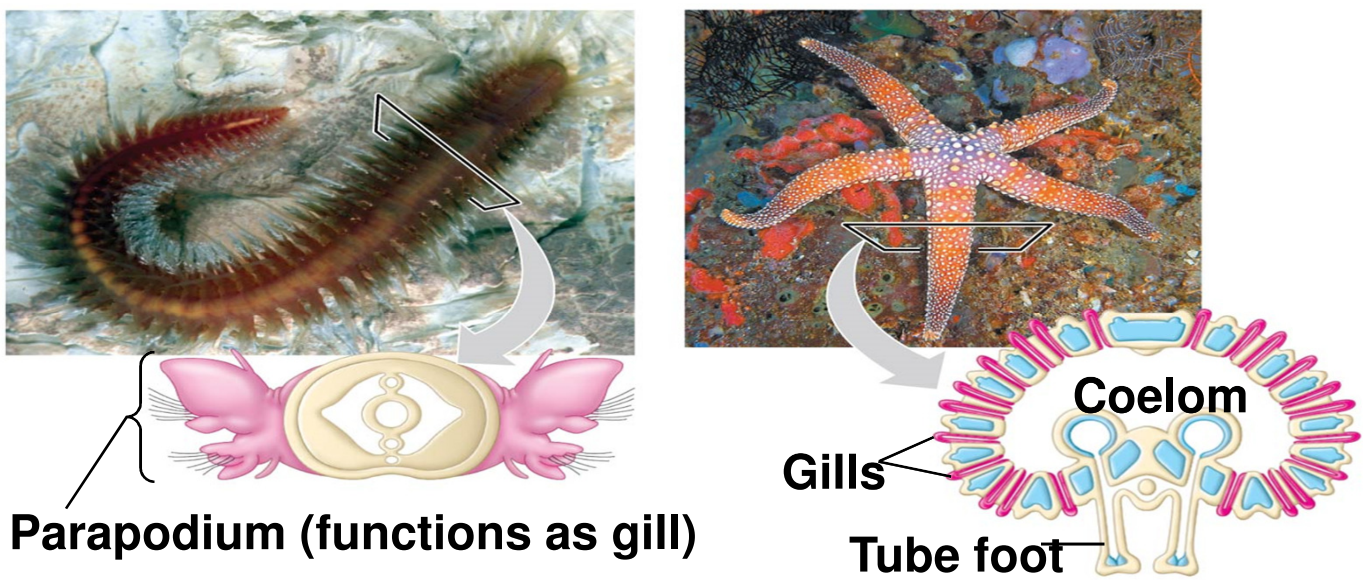
- A **heart attack,** or myocardial infarction, is the death of cardiac muscle tissue resulting from blockage of one or more coronary arteries
  - Coronary arteries supply oxygen-rich blood to the heart muscle
- A **stroke** is the death of nervous tissue in the brain, usually resulting from rupture or blockage of arteries in the head
- **Hypertension** (high blood pressure) contributes to the risk of heart attack and stroke
  - Can be reduced by dietary changes, exercise, medication, or some combination of these

Concept 34.5: Gas exchange occurs across specialized respiratory surfaces

- **Gas exchange** is the uptake of molecular O_2 from the environment and the discharge of CO_2 to the environment
- **Partial pressure** is the pressure exerted by a particular gas in a mixture of gases
  - A gas always undergoes net diffusion from a region of higher partial pressure to a region of lower partial pressure

Respiratory Media

- Obtaining O_2 from water requires greater energy expenditure than air breathing
  - The warmer and saltier that water is, the less dissolved O_2 it can hold
- Aquatic animals have a variety of adaptations to improve efficiency in gas exchange



(a) Marine worm (b) Sea star

Respiratory Surfaces

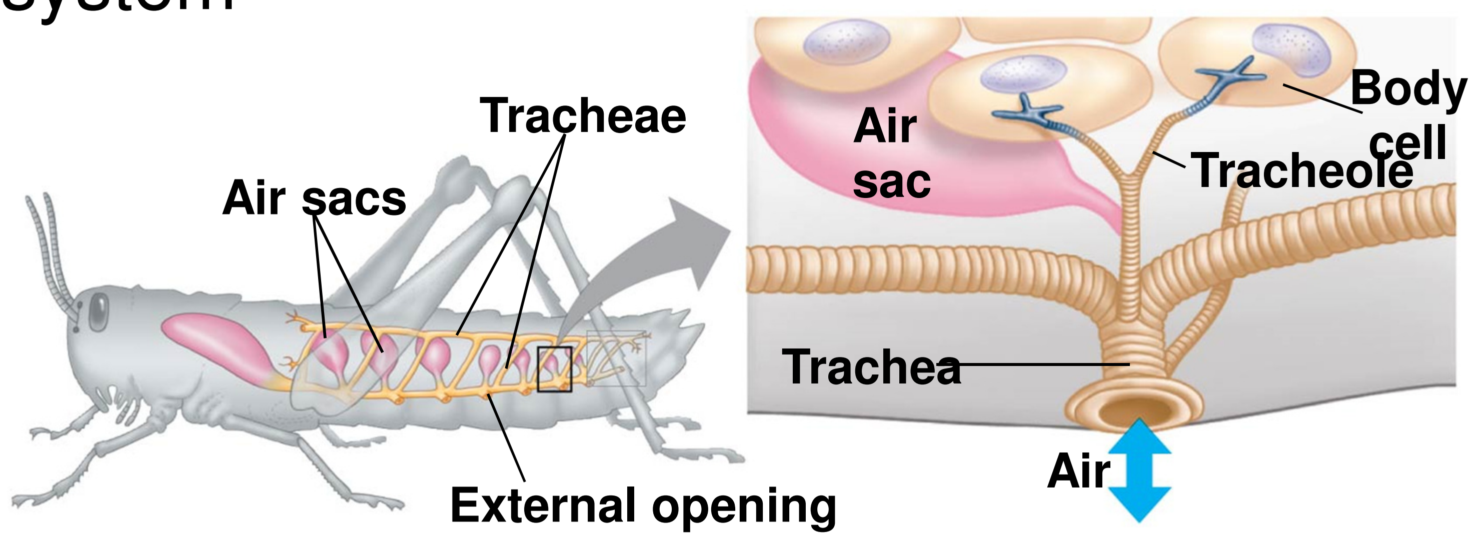
- Gas exchange across respiratory surfaces takes place by diffusion
- Respiratory surfaces tend to be large and thin and are always moist
- Respiratory surfaces vary by animal and can include the skin or extensively folded or branched organs like gills, tracheae, and lungs

Gills in Aquatic Animals

- Gills are outfoldings of the body that create a large surface area for gas exchange
- **Ventilation** is the movement of the respiratory medium over the respiratory surface
  - Maintains the necessary partial pressure gradients of O_2 and CO_2 across the gills
  - Aquatic animals move through water or move water over their gills for ventilation
- Fish gills use a **countercurrent exchange** system, where blood flows in the opposite direction to water passing over the gills

Tracheal Systems in Insects

- The **tracheal system** of insects consists of a network of air tubes that branch throughout the body
  - Can transport O_2 and CO_2 without the participation of the animal's open circulatory system



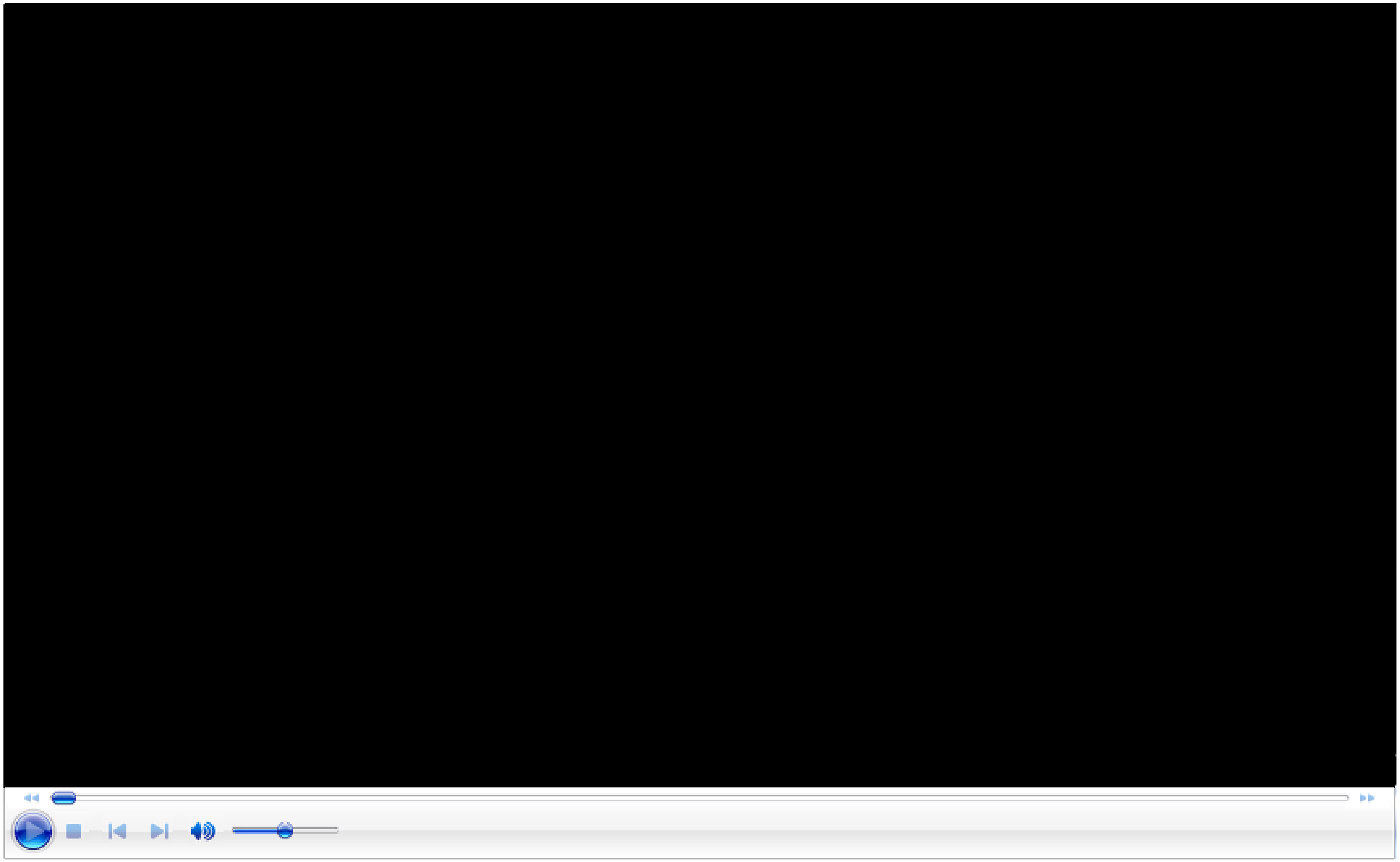
Lungs

- **Lungs** are an infolding of the body surface, usually divided into numerous pockets
  - Localized respiratory organs, unlike tracheal systems which branch throughout entire insect body
- The circulatory system (open and closed) transports gases between the lungs and the rest of the body

Mammalian Respiratory Systems: A Closer Look

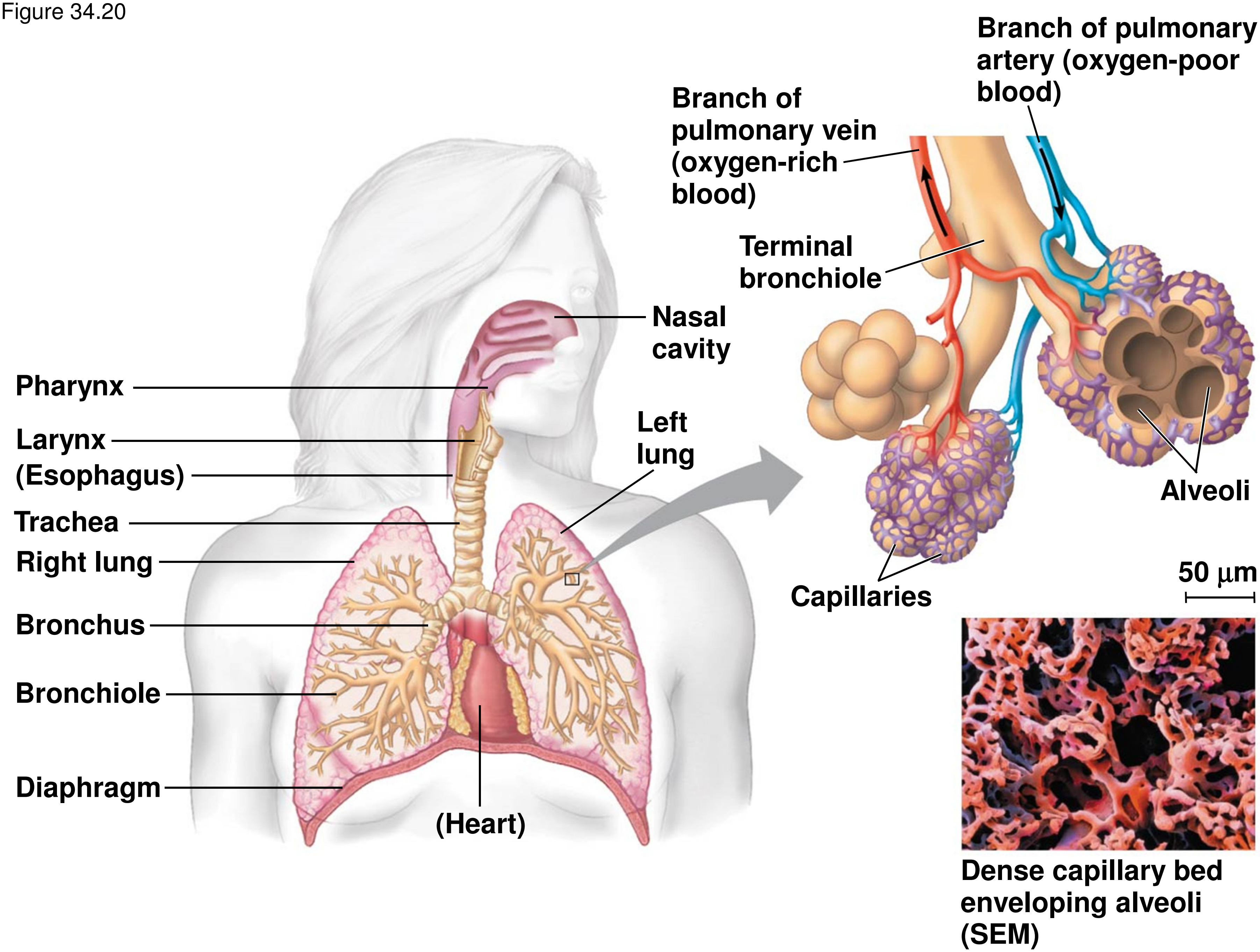
- A system of branching ducts conveys air to the lungs
- Air inhaled through the nostrils is warmed, humidified, and sampled for odors
- The pharynx directs air to the lungs and food to the stomach
  - Swallowing tips the epiglottis over the glottis in the pharynx to prevent food from entering the **trachea**, or windpipe
- Air passes through the pharynx, larynx, trachea, bronchi, and bronchioles to the alveoli, where gas exchange occurs

- Exhaled air passes over the vocal cords in the **larynx** to create sounds
- Trachea branches into 2 **bronchi**
    - One leading to each lung
- Bronchi branch into finer tubes called *bronchioles*
- Air sacs at the tips of the bronchioles are called **alveoli**
    - Where gas exchange takes place
        - Oxygen diffuses through the moist film of the epithelium and into capillaries
        - Carbon dioxide diffuses from the capillaries across the epithelium and into the air space



Video: Gas Exchange

Figure 34.20



Branch of pulmonary artery (oxygen-poor blood)
Branch of pulmonary vein (oxygen-rich blood)
Terminal bronchiole
Nasal cavity
Pharynx
Larynx
(Esophagus)
Left lung
Trachea
Right lung
Bronchus
Bronchiole
Diaphragm
(Heart)
Alveoli
Capillaries
50 µm
Dense capillary bed enveloping alveoli (SEM)

- Cilia and mucus line the epithelium of the air ducts
  - Traps dust, pollen, etc. and moves the particles up to the pharynx
- Alveoli lack cilia and are susceptible to contamination

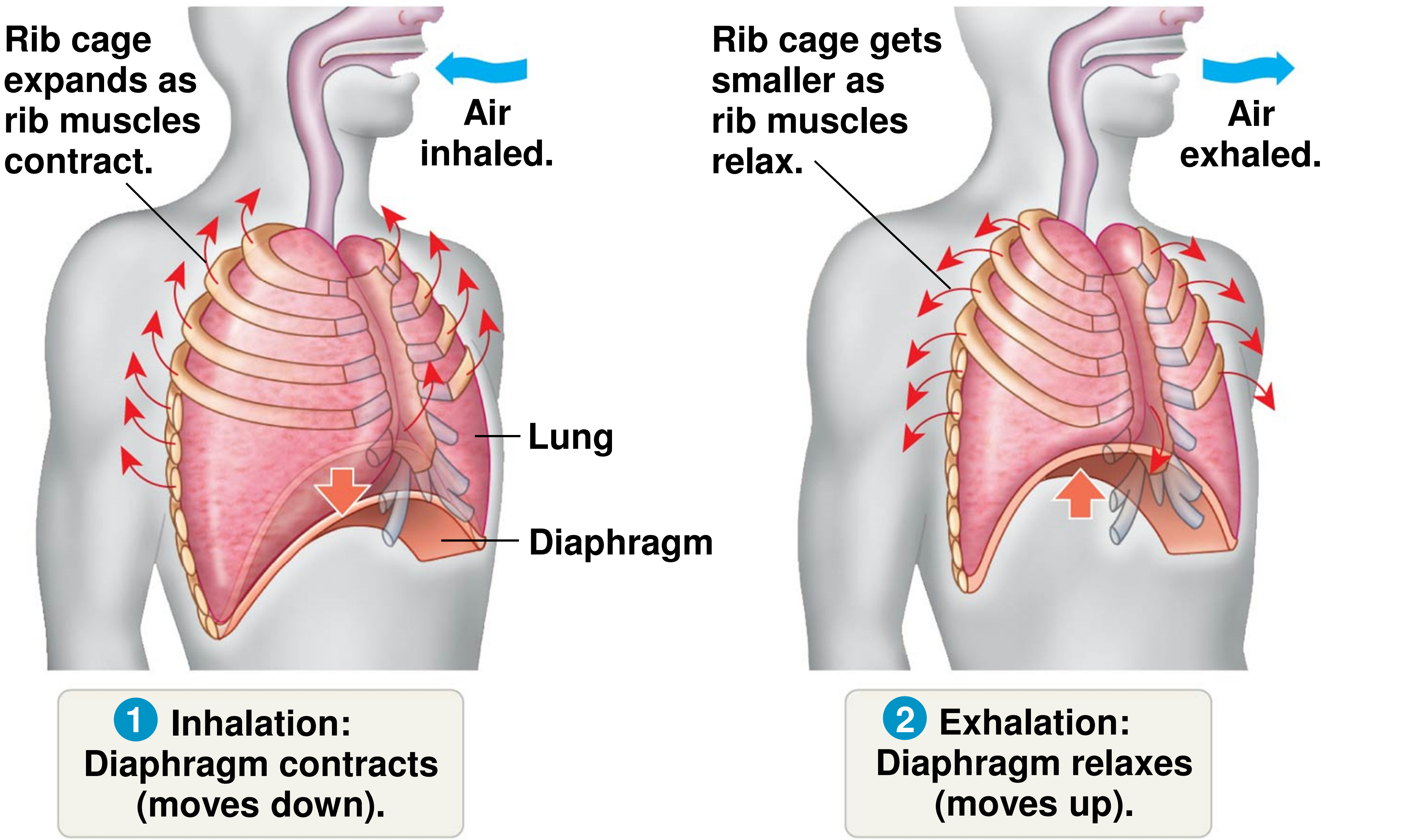
Concept 34.6: Breathing ventilates the lungs

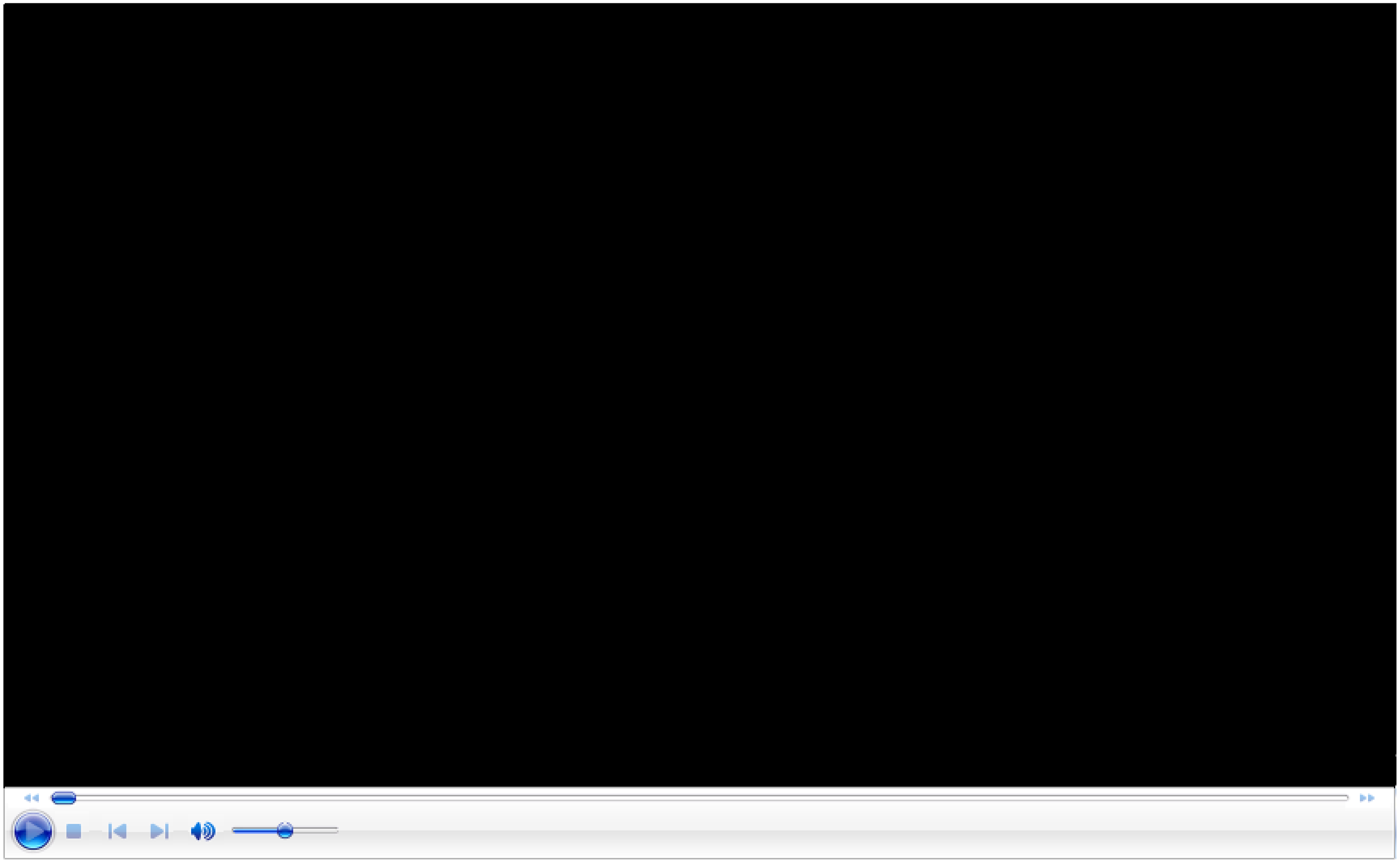
- The process that ventilates the lungs is **breathing**
  - The alternate inhalation and exhalation of air
- An amphibian such as a frog ventilates its lungs by **positive pressure breathing**, which forces air down the trachea
- Birds have eight or nine air sacs that function as bellows that keep air flowing through the lungs
  - Air passes through the lungs of birds in one direction only
  - Passage of air through the entire system—lungs and air sacs—requires two cycles in inhalation and exhalation

How a Mammal Breathes

- Mammals ventilate their lungs by **negative pressure breathing**, which pulls air into the lungs
  - During inhalation, air pressure in lungs is lowered by actively expanding thoracic cavity through muscle contraction
    - Lung volume increases as the rib muscles and **diaphragm** contract
  - During exhalation, muscles relax, cavity's volume is reduced, and air pressure increases

Figure 34.22


Rib cage expands as rib muscles contract.
Air inhaled.
Lung
Diaphragm
1 Inhalation: Diaphragm contracts (moves down).
Rib cage gets smaller as rib muscles relax.
Air exhaled.
2 Exhalation: Diaphragm relaxes (moves up).



Video: Gas Exchange

- **Tidal volume** is the volume of air inhaled with each breath
- The maximum tidal volume is the **vital capacity**
- After exhalation, a **residual volume** of air remains in the lungs
- Each inhalation mixes fresh air with oxygen-depleted residual air
  - Mammals don’t function as well as birds at high altitude

Control of Breathing in Humans

- In humans, the main breathing control center consists of neural circuits in the medulla oblongata, near the base of the brain
  - The medulla uses pH as an indicator of blood CO_2
  - Regulates the rate and depth of breathing in response to pH changes
- The medulla adjusts breathing rate and depth to match metabolic demands